What's New in Exoplanet Technology?

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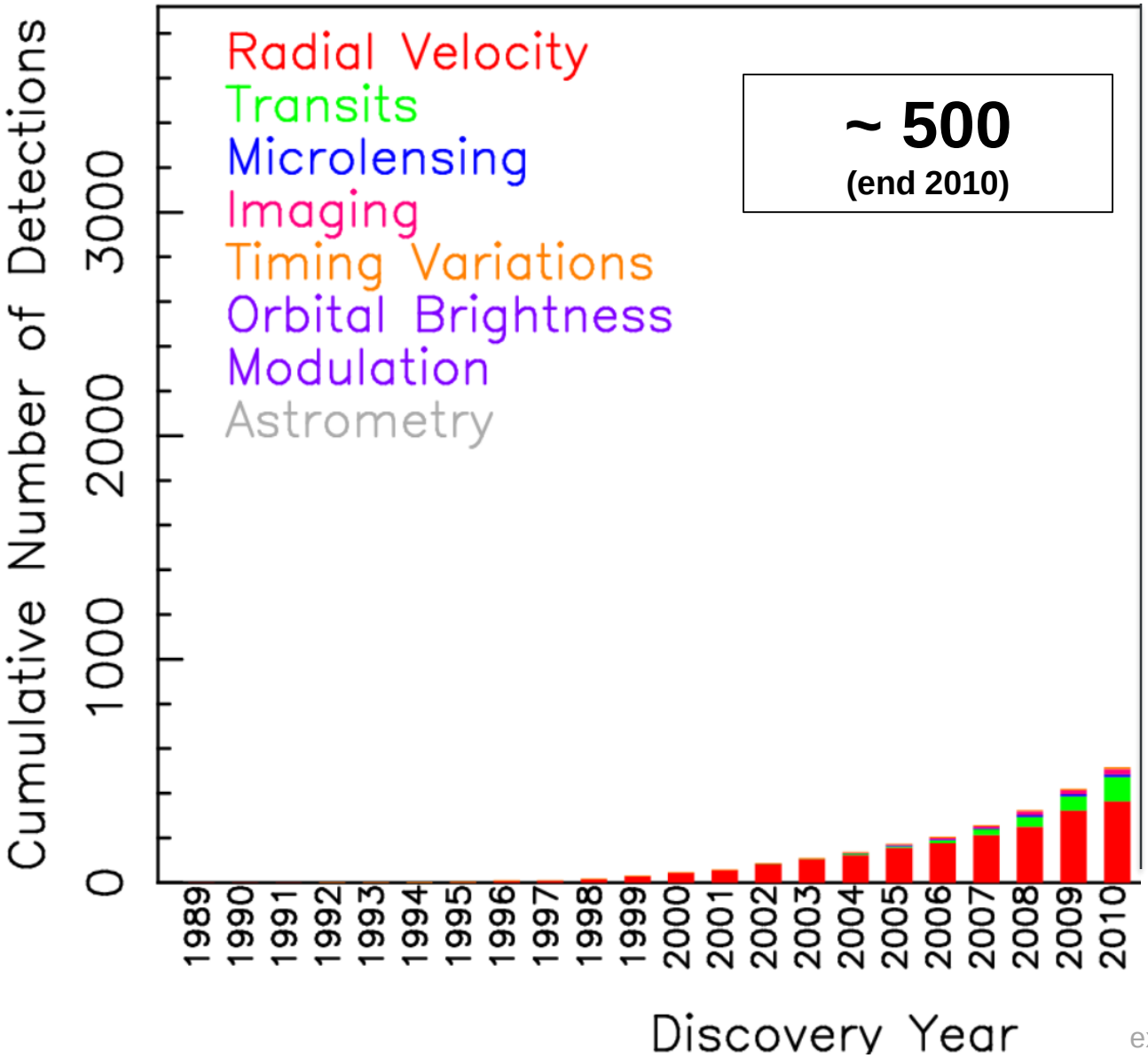
The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.



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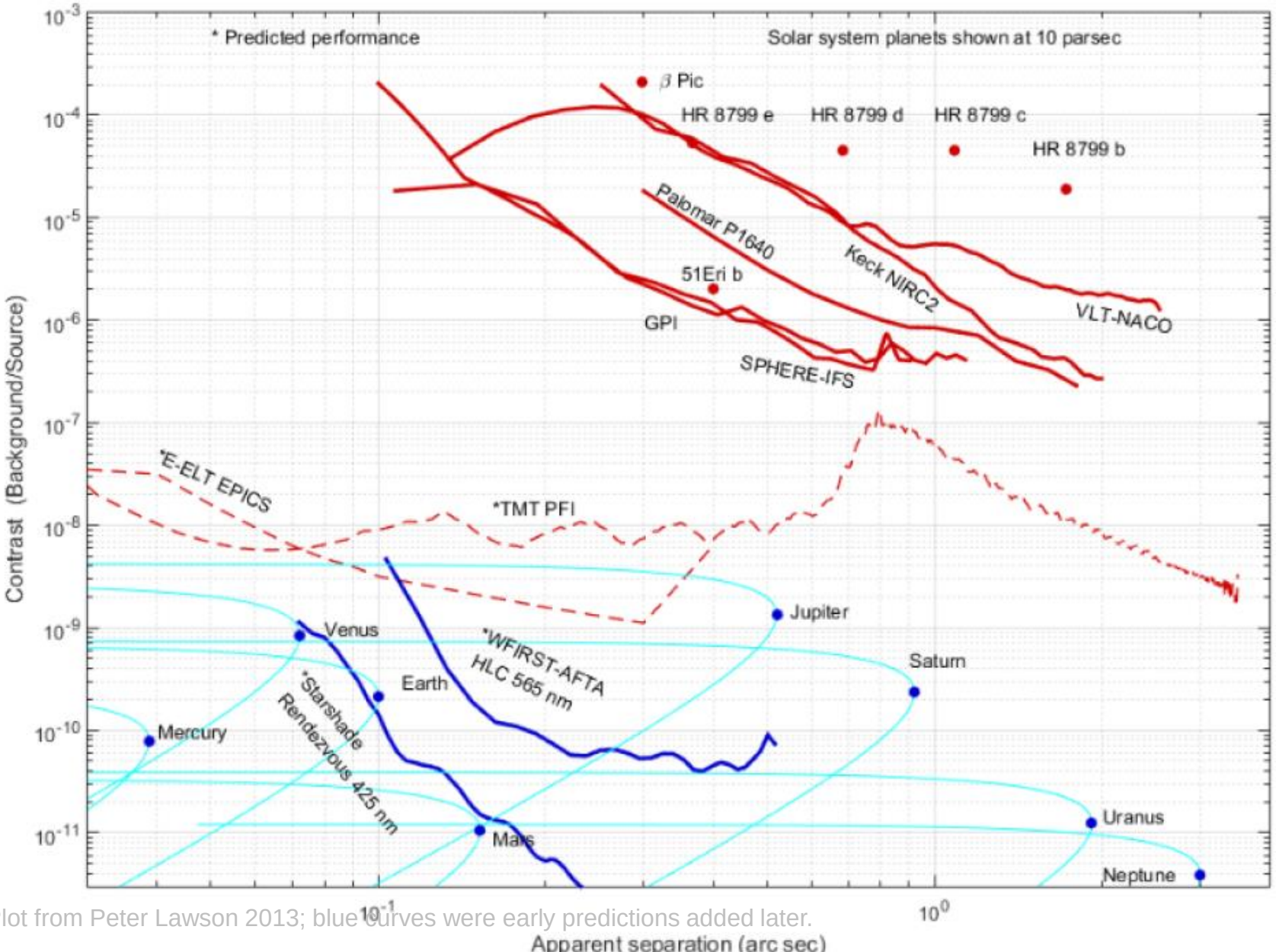
Contrast vs Separation

Figure from 2013



Plot from Peter Lawson 2013; blue curves were early predictions added later.

Coronagraph State-of-the-Art in 2009

Lab Demonstrations

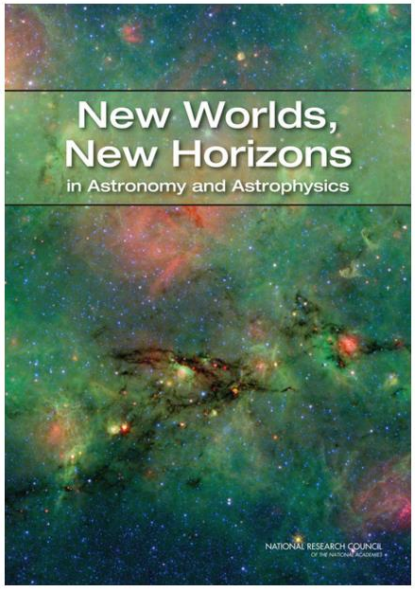
Parameter	Hybrid Lyot (linear mask)	PIAA	Vortex	Visible Nuller
Raw contrast (at IWA)	1.2×10^{-10}	2×10^{-7}	10^{-8}	10^{-8}
Bandwidth	2%	mono	mono	10nm/630nm
Working Angle	4 - 10 λ/D	1.65 - 4.4 λ/D	2.5 – 12 λ/D	2 – 4 λ/D
Reference	Trauger and Traub (2007) Nature	TDEM-09 whitepaper (Guyon)	TDEM-10 whitepaper (Serabyn)	Lyon et al (2009) SPIE paper

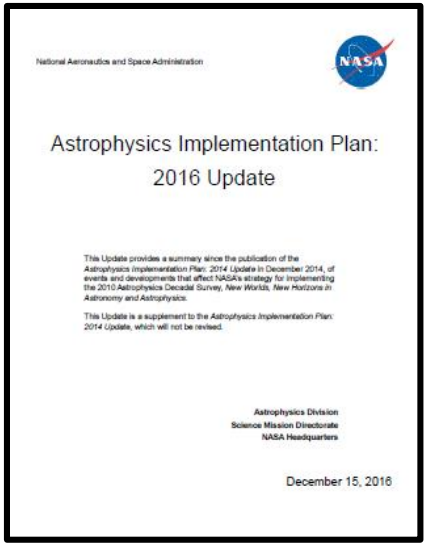
2010 Decadal Survey Recommendations

… and NASA Response

Decadal Survey Recommendation	NASA Actions
Large-scale 1. WFIRST	In Phase A, launch in mid-2020s (see Section 4)
Large-Scale 2. Augmentation to Explorer Program	Executing 4 Announcements of Opportunity (AOs) per decade (see Section 5)
Large-Scale 3. LISA	Partnering on ESA's space-based gravitational wave observatory (see Section 6.1)
Large-Scale 4. IXO	Partnering on ESA's Athena X-ray observatory (see Section 6.2)
Medium-Scale 1. New Worlds Technology Development Program	WFIRST coronagraph; starshade and coronagraph technology development; Doppler spectrograph on WIYN telescope; exozodiacal dust survey with LBTI (see Section 7.1)
Medium-Scale 2. Inflation Probe Technology Development Program	Multiple balloon-borne investigations plus SAT investments (see Section 7.2)
Small-Scale. Research Program Augmentations	R&A as of FY2016 up 20% from FY2010; increase not targeted except TCAN (see Section 7.3)
Small-Scale. Intermediate Technology Development Augmentation	Initiated Strategic Astrophysics Technology program; focused on identified strategic missions
Small-Scale. SPICA (U.S. contribution)	Not supported as a strategic contribution; candidate for Explorer Mission of Opportunity

Table 1. Recommended space activities of the 2010 Decadal Survey supported by the FY 2016 NASA Appropriation, the FY 2017 President's Budget Request, and its notional out year planning budget.





APD Implementation Plan (2012, 2014, 2016)

2010 Decadal Survey Recommendation

Medium Scale Category

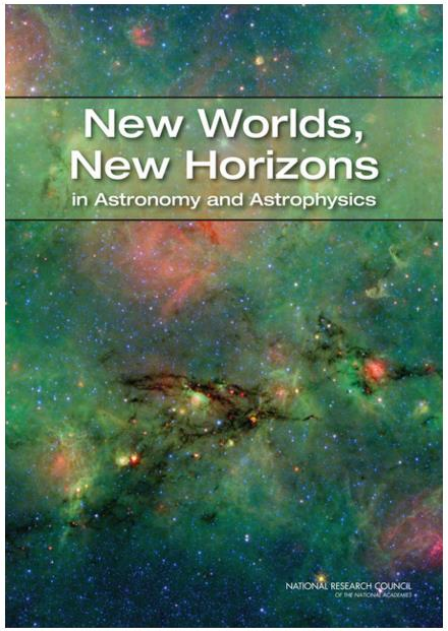
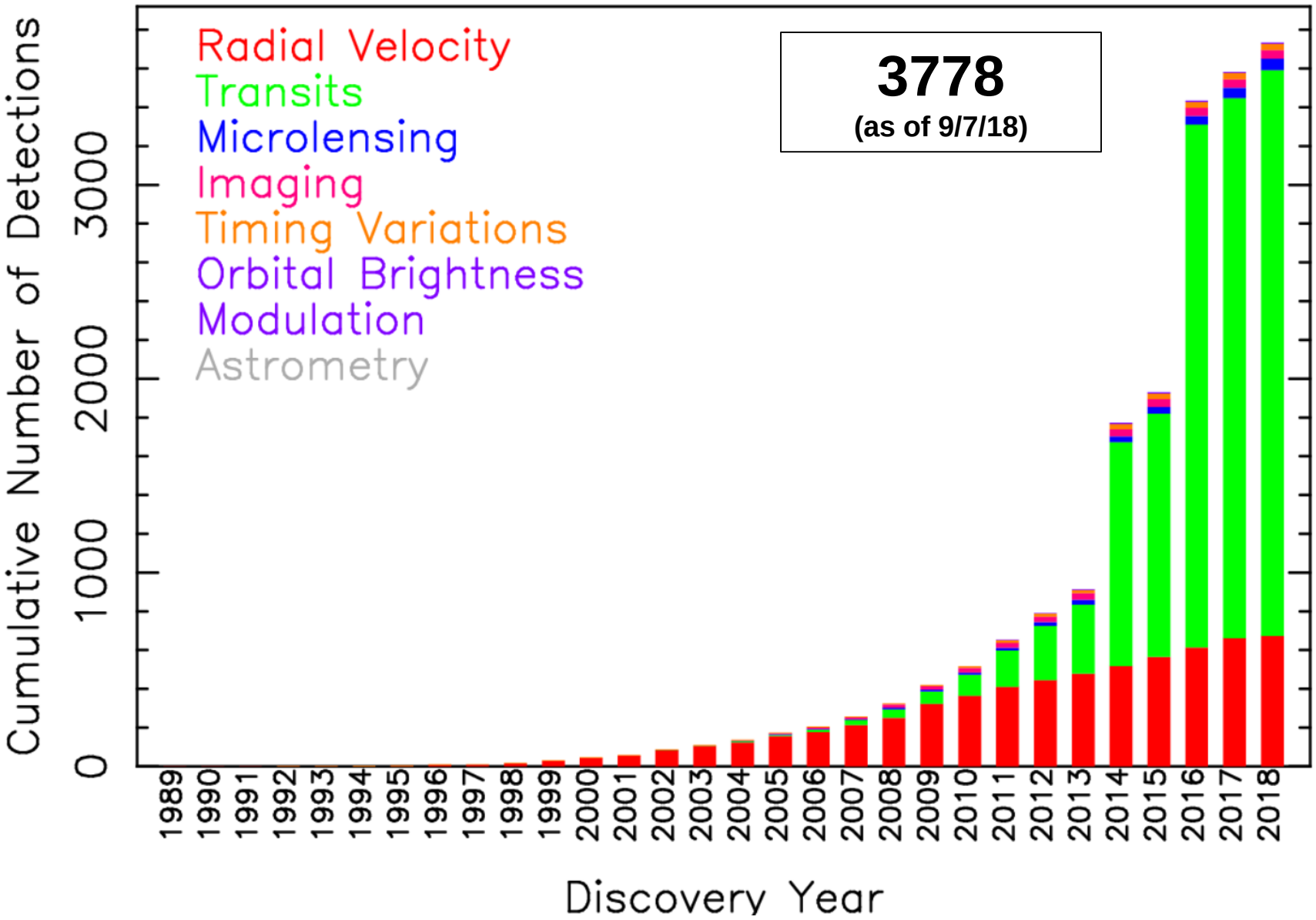


TABLE ES.4 Space: Recommended Activities—Medium-Scale (Priority Order)

Recommendation	Science	Appraisal of Costs[a]
1. New Worlds Technology Development Program	Preparation for a planet-imaging mission beyond 2020, including precursor science activities	$100M to $200M
2. Inflation Probe Technology Development Program	Cosmic microwave background (CMB)/ inflation technology development and preparation for a possible mission beyond 2020	$60M to $200M

"…high-priority science areas for which mid-term investments are needed beginning early in the decade, including development of a variety of technologies for exoplanet imaging, such as coronagraphs, interferometers, and starshades, leading to possible late-decade down-selecting."



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We now know that in our Galaxy…

Planets are common
(> 1 per star)

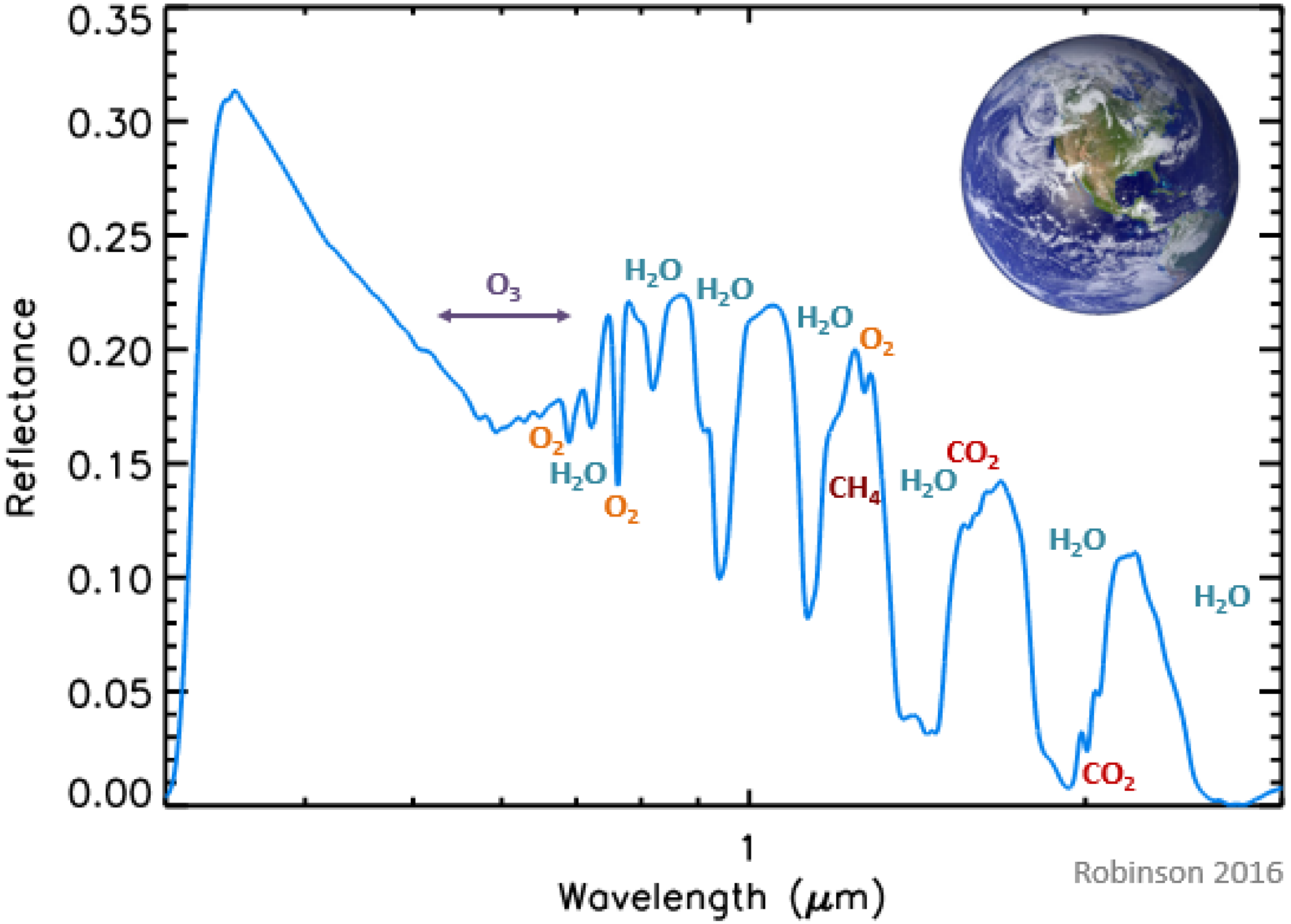
Planets with sizes
0.5-2 times Earth
are the most common

Earth-size planets in the
Habitable Zone are
common

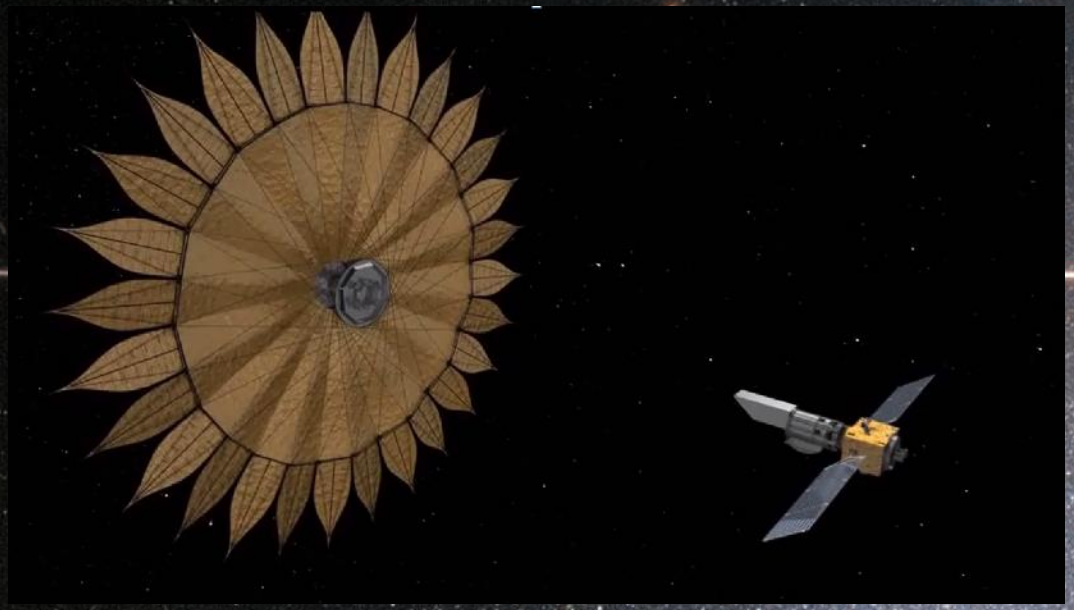
…we're ready for the search for life

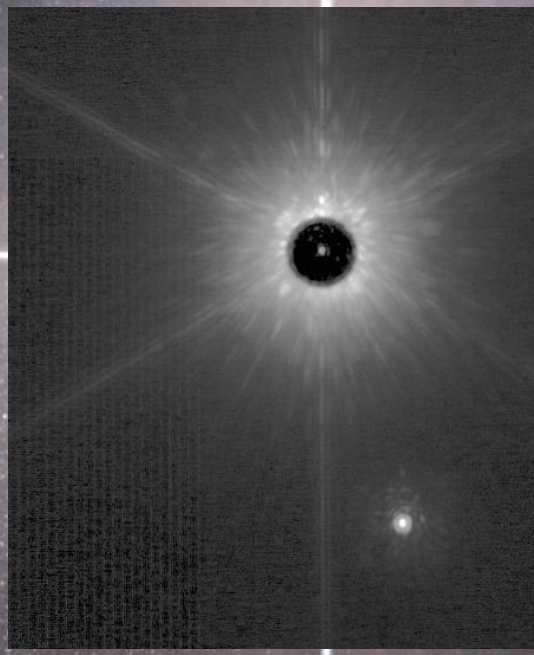
Potential Biosignature Gases

Spectral Lines

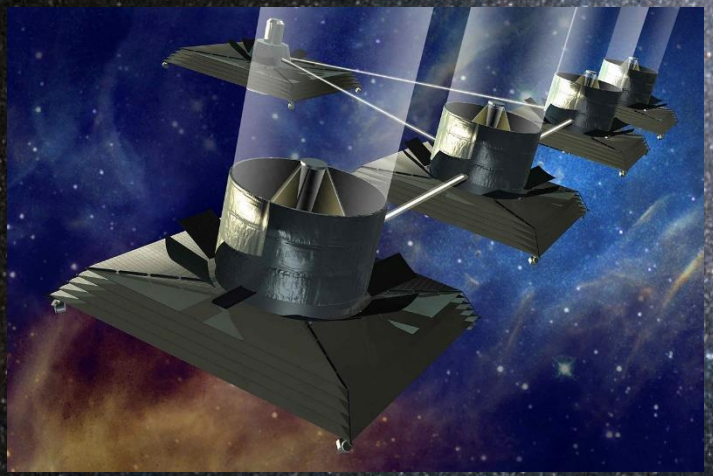


External Occulters (Starshades)

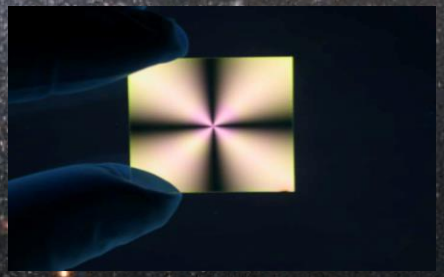




Nulling Interferometry



Internal Occulters (Coronagraphs)



NASA Response to Medium Scale Rec #1

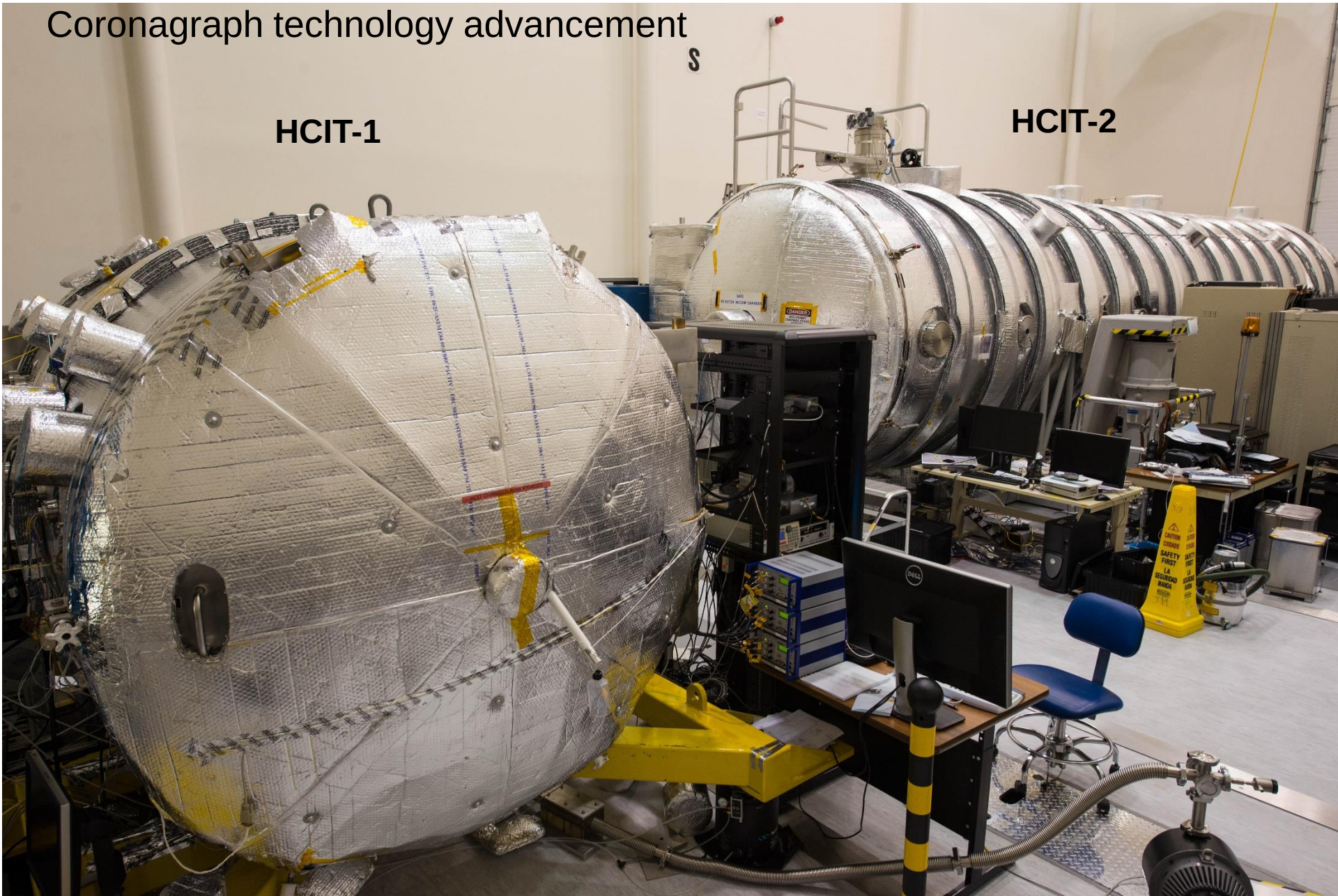
Targeted technology grants

- **Continued use of competitively selected individual investigator awards issued under the Astrophysics Research and Analysis (APRA) and Strategic Astrophysics Technology (SAT) programs.**
  - APRA addresses early-TRL technologies (1-2)
  - SAT addresses mid-TRL technologies (3-5)
    - Within the SAT, **Technology Development for Exoplanet Missions** (TDEM) primarily focuses on exoplanet technologies.

- **About 40 awards since 2010 have advanced the technology readiness of starshades, coronagraphs, and their associated supporting technologies.**

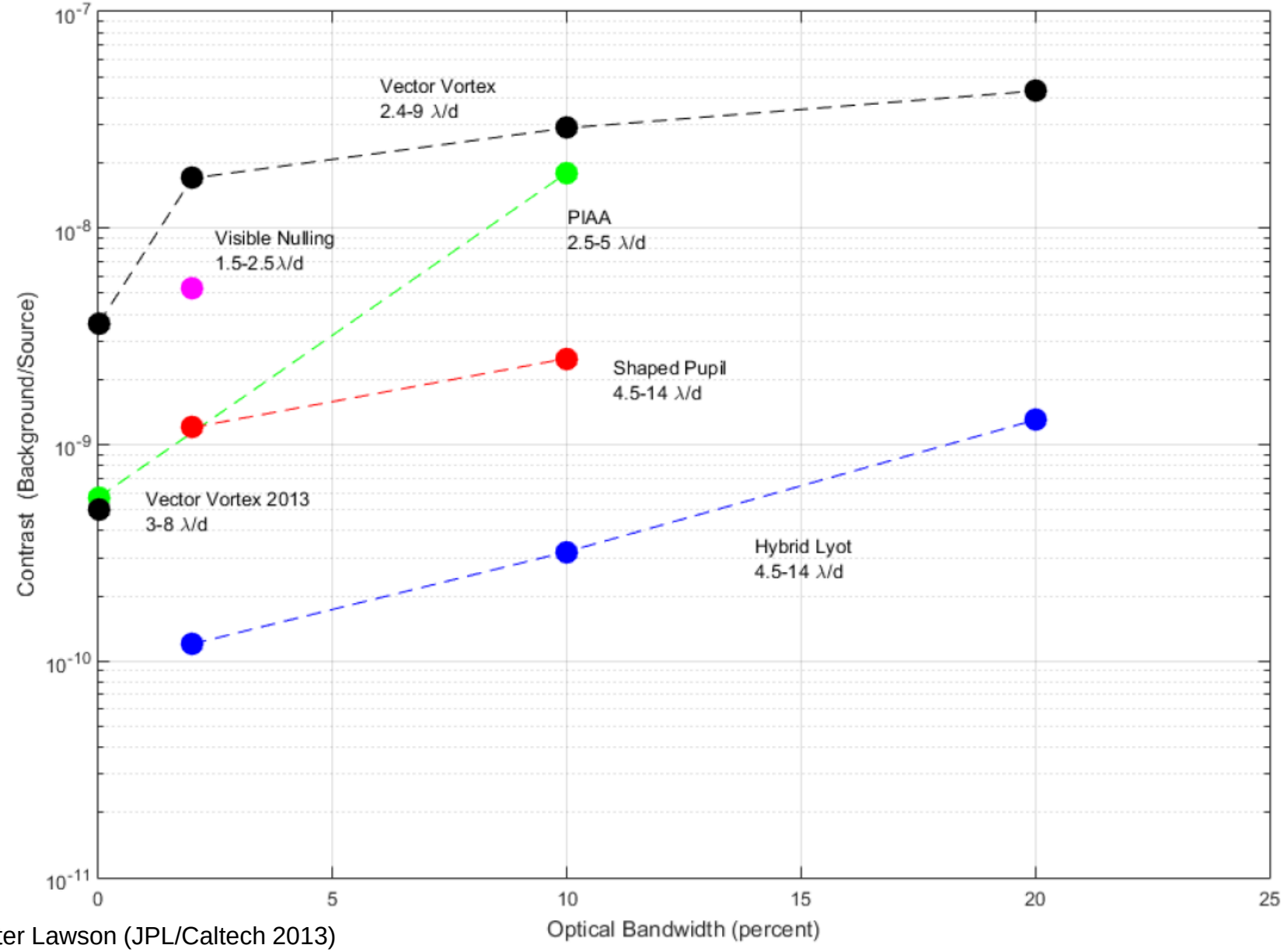
High Contrast Imaging Testbed Facility (JPL)

Coronagraph technology advancement



Coronagraph Progress for Space

Contrast vs. Bandwidth



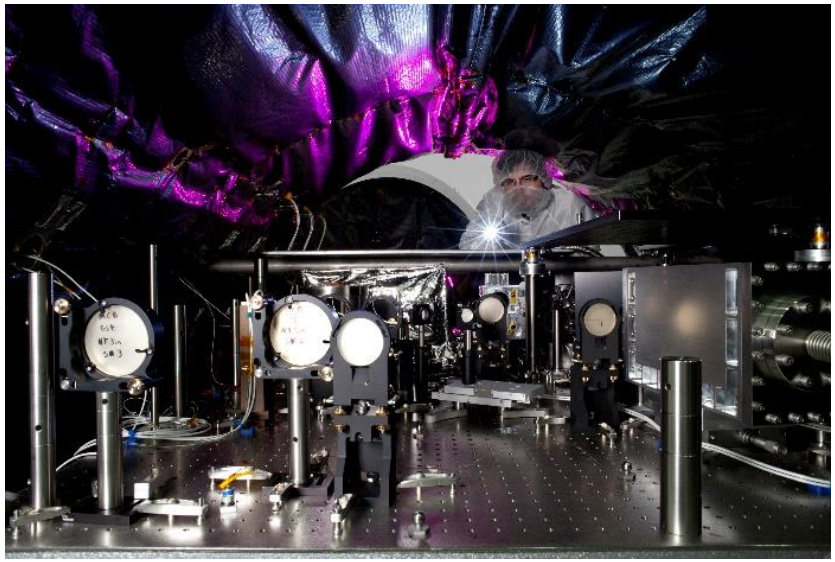
Peter Lawson (JPL/Caltech 2013)

Coronagraph Progress for Space

- **In 2013, coronagraphy was "spun off" from the ExEP to the WFIRST project to support technology advancement for their coronagraph instrument.**

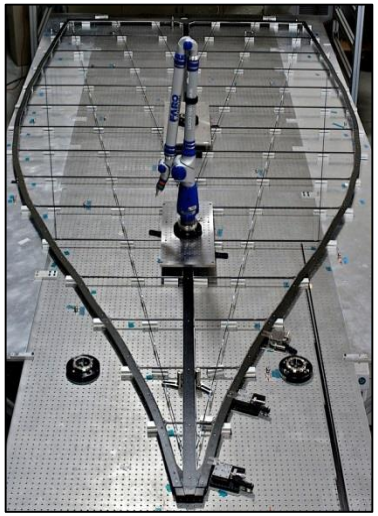
- **Achieved TRL 5 in 2017**

- **Advancing component technologies**
  - Deformable mirrors
  - Ultar-low noise detectors (EMCCDs)
  - Low-order wavefront sensors
  - Post-processing



Starshade Progress

- **Starshade advanced through TDEM Program:**
  - petal manufacturing
  - optical demonstrations
  - inner disk deployment



- In 2016, the starshade was spun off to establish a **starshade technology development activity.**

Petal Unfurler Testbed 2.0

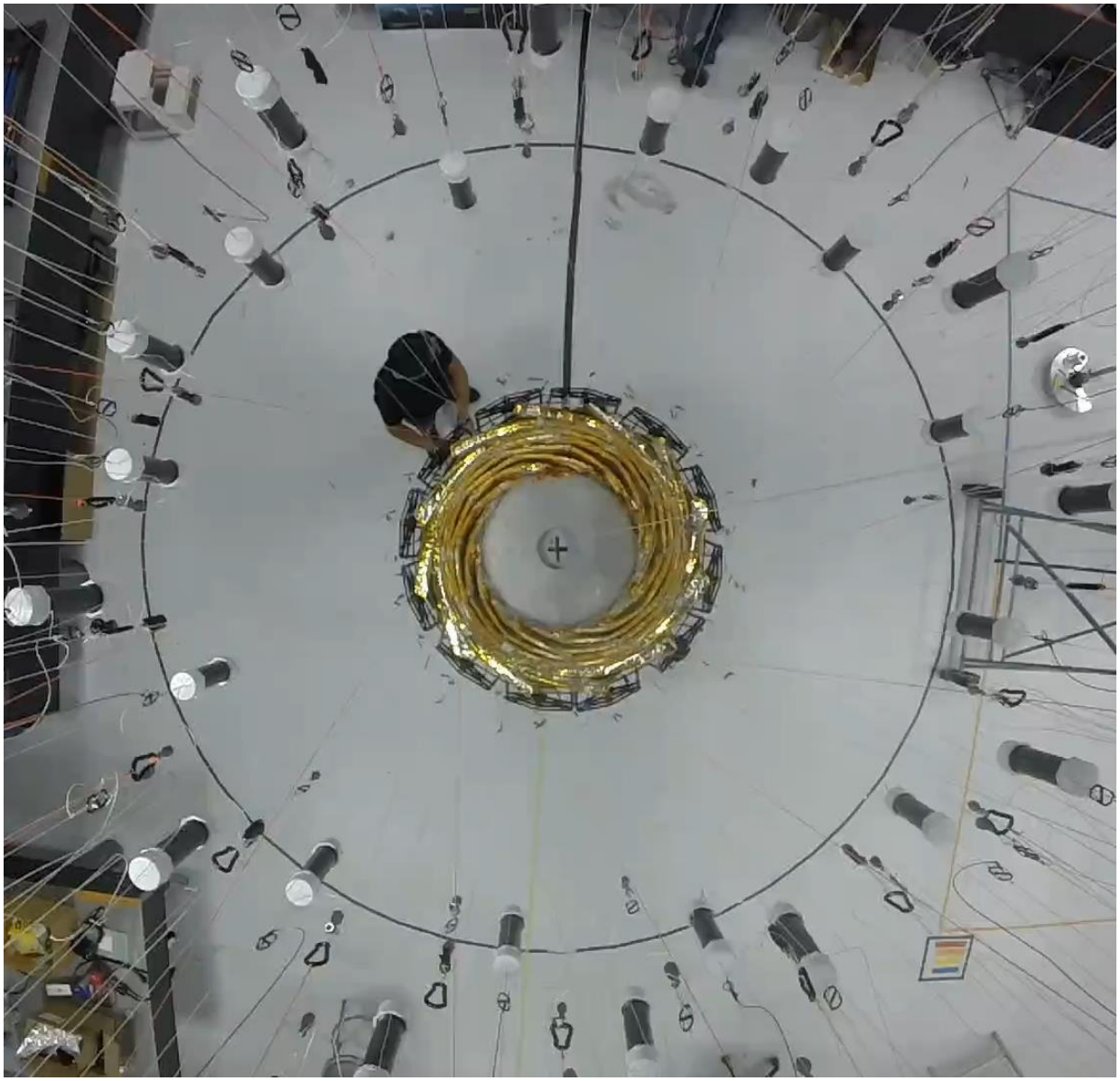
JPL plus Tendeg Gravity Offloader

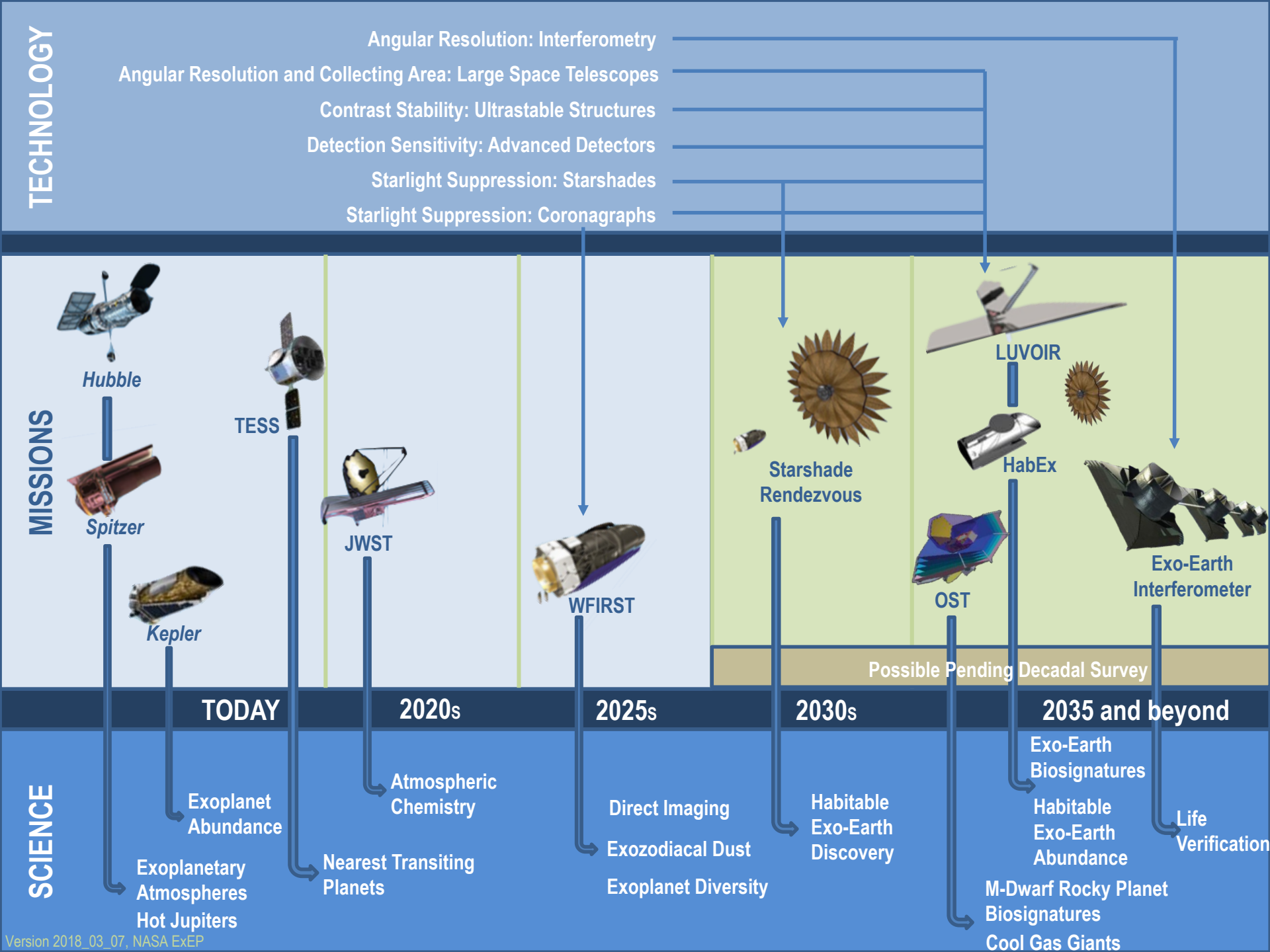
Inner Disk Deployment

10 m Prototype Demonstration (JPL)

Optical Shield Deployment

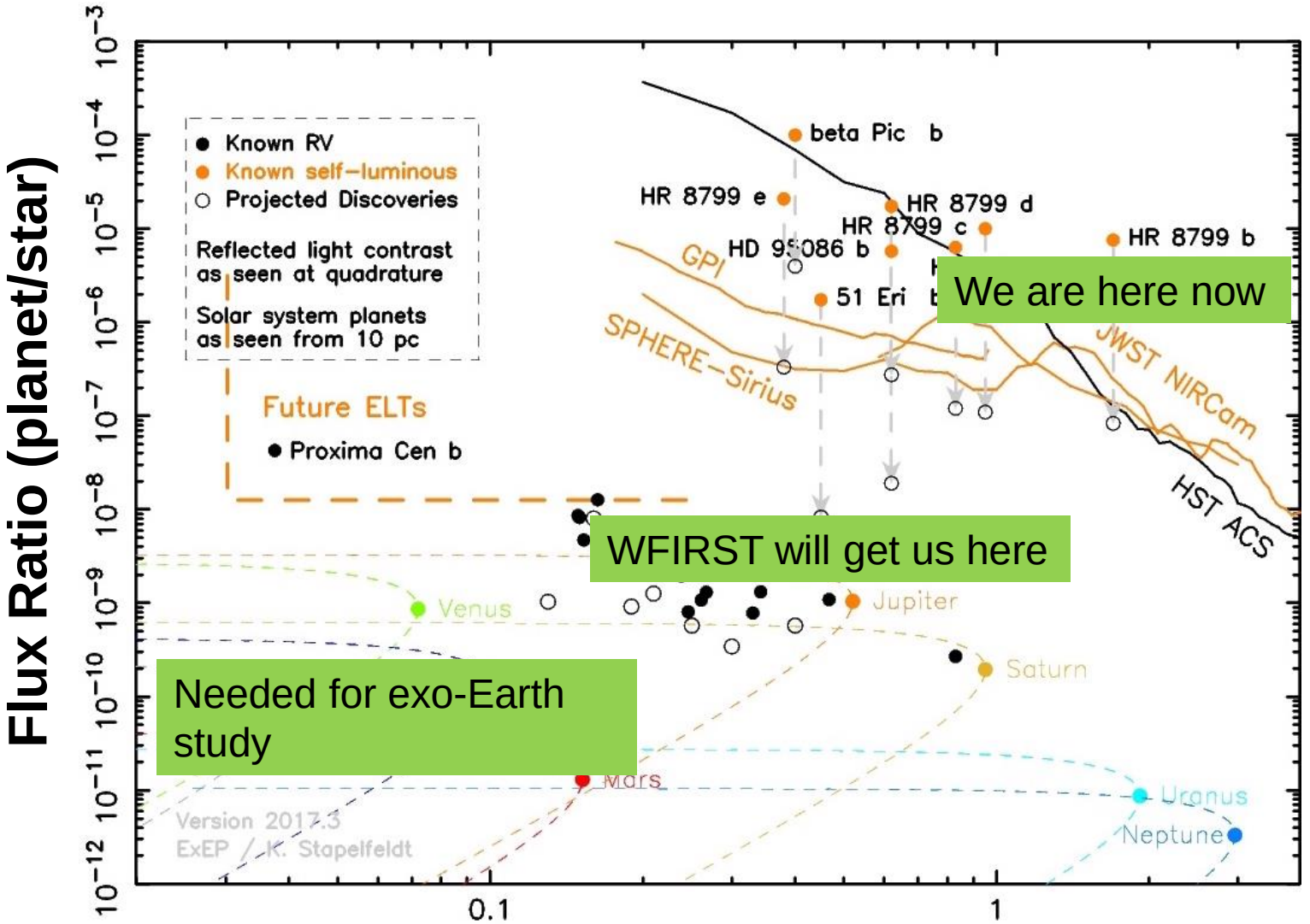
5 m Prototype Demonstration





Version 2018_03_07, NASA ExEP

Still a Way to go to Directly Imaging Exo-Earths



Active TDEMS

- **Advancing Coronagraphy to < 10^{-9}**
  - Vortex (PI Gene Serabyn/JPL)
  - Hybrid Lyot (PI John Trauger/JPL)
  - PIAA (PI Rus Belikov/ARC)
  - APLC (PI Remi Soummer/STScI)
  - Multi-star wavefront control (PI Rus Belikov/ARC)

- **Understanding and Minimizing the Effects of Polarization**
  - Jim Breckinridge (Caltech) and UA team performing independent polarization ray-trace of the HabEx and LUVOIR optics

- **Advancing a Second 10^{-10} Deformable Mirror**
  - MEMS 32x32 (PI Paul Bierden/Boston Mocromachines)
  - MEMS 50x50 (SBIR)

Segmented Mirror Technology Program

- Telescope apertures will continue to get larger and structural and wavefront error stability will be challenging when working with coronagraphs.
- Industry awards created to address system-level design and modeling challenges for achieving picometer-level wavefront error stability in a segmented UV/V/NIR space telescope.

Ultra-Stable Large Telescope Research and Analysis (ULTRA), PI Scott Knight (Ball Aerospace)

System-Level Segmented Telescope Design
PI Larry Dewell (Lockheed Martin)

Segmented Coronagraph Design and Analysis

- **Purpose: Ensure there is at least one coronagraph architecture that can meet the contrast requirements of future large segmented space telescopes to directly image and characterize exo-Earths.**
- **Promising designs delivered of the APLC (STScI/GSFC) and Vortex (Caltech/JPL) teams; HLC (JPL) catching up, PIAACMC (UA/Ames) and VNC GSFC) struggling to meet metrics.**
- **Lessons learned:**
  - Big dropoff in throughput seen when secondary obscuration exceeds 30% of the primary mirror diameter
  - Angular size of the star problematic for some coronagraphs
  - Segmentation gaps are not a major problem (if small)
  - Central obscuration biggest challenge

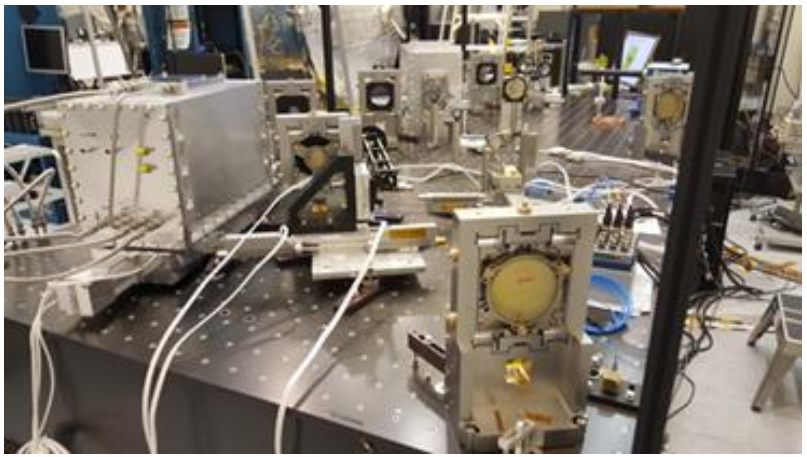
- **Next steps**
  - Test new apodization masks in testbeds (not yet vacuum)
  - Test the robustness of the designs to wavefront errors and tolerancing: Do these coronagraphs put constraints on the telescopes that are unrealistic?

Decadal Survey Testbed

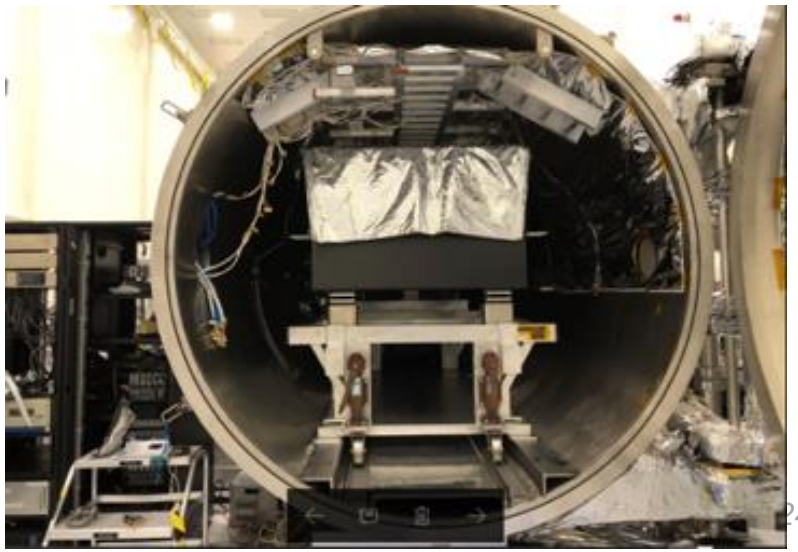
Advancing the next generation of coronagraphs

- **Purpose:**
  - Develop a testbed that is sufficiently low noise to demonstrate next-generation coronagraphs reach 10^{-10} contrast
  - To be made available to community
- **Currently Commissioning with a clear aperture plus Hybrid Lyot**
  - **Plan is to reach a new contrast record by the end of this CY (≤ 10^{-10})**
- **In CY19, add a segmented/obscured mask to simulate the segmentation pattern of a large space telescope mirror**

Assembled optical bench

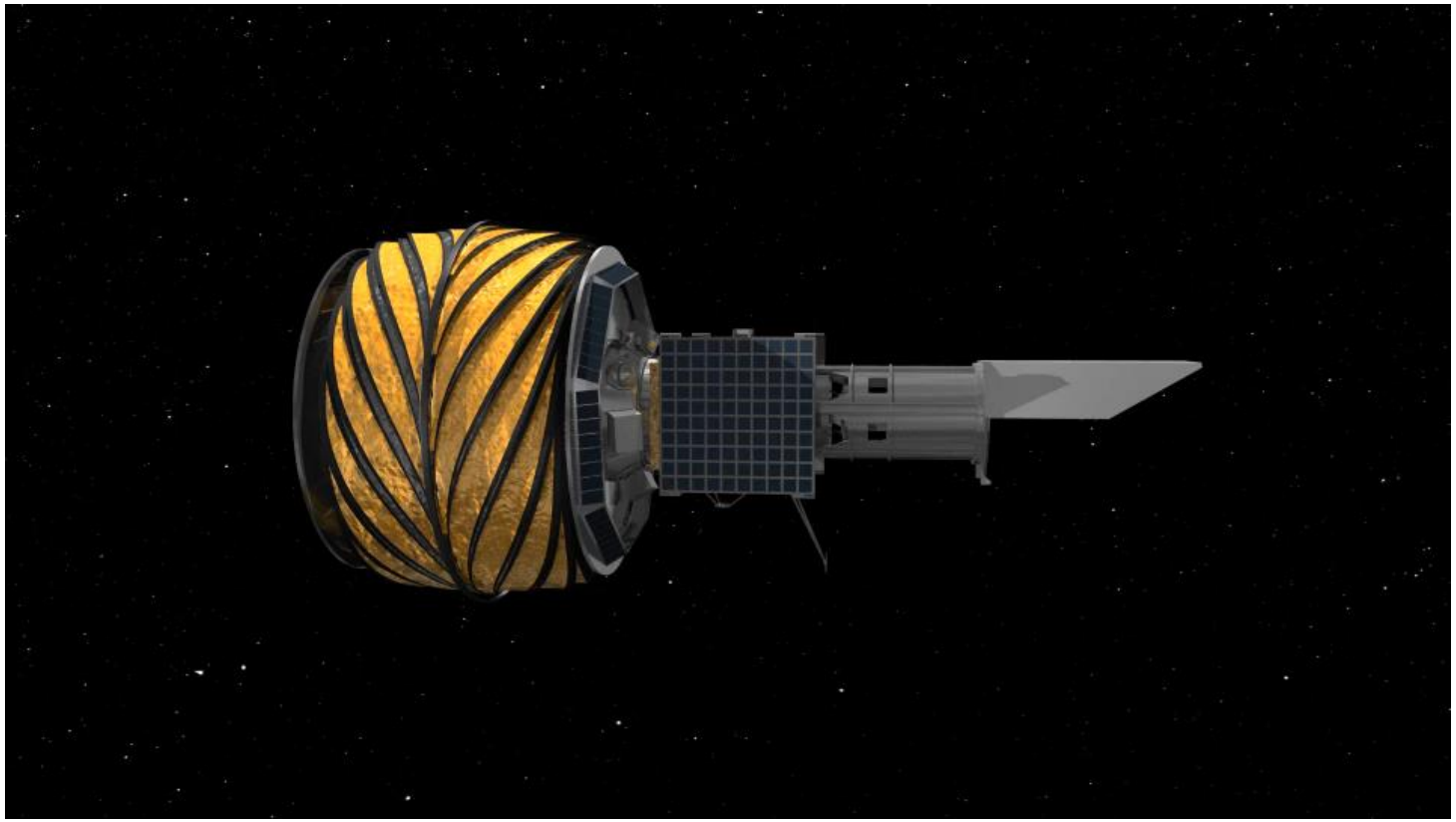


Installed in the chamber: June 2018



Starshade Deployment Trade Study Completed

Wrapped petal architecture selected



- **Technology Development Plan advanced to bring the starshade to TRL 5 by early 2020s.**
  - ❖ Review of milestones by ExoTAC in August
  - ❖ Delivery of Plan for NASA HQ approval in September

Inputs to National Academies Exoplanet and Astrobiology Strategy Committees

- Whitepaper submitted to the Astrobiology Science Strategy: Siegler et al. *Technology Needs for Detecting Life Beyond the Solar System: A White Paper in Support of the Astrobiology Science Strategy* arXiv:1801.07811

- Whitepaper submitted to the National Academies Exoplanet Science Strategy: Crill et al. *Key Technology Challenges for the Study of Exoplanets and the Search for Habitable Worlds* arXiv:1803.04457

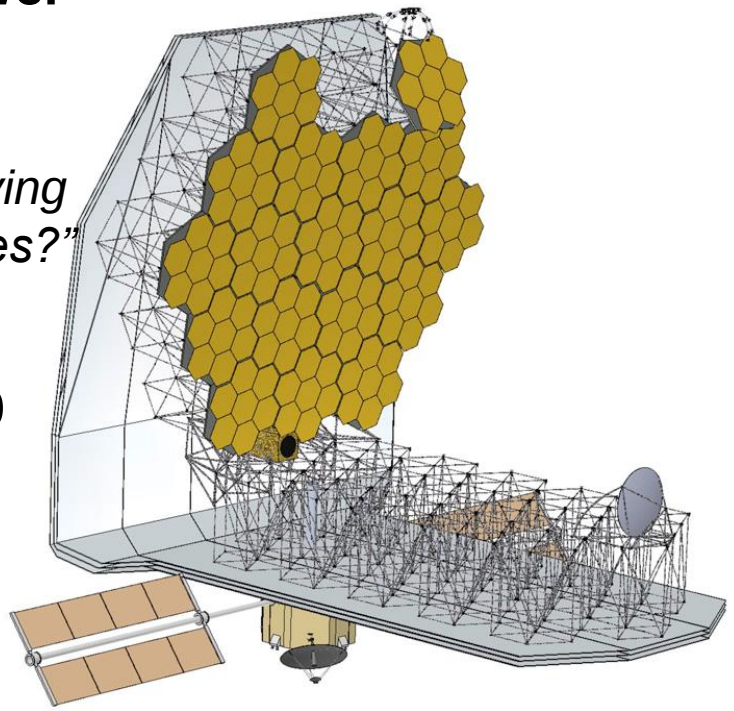
- Briefed the NAS Exoplanet Science Strategy committee at their Irvine meeting on April 20, 2018 on “Exoplanet Technology Gaps” https://exoplanets.nasa.gov/internal_resources/893/

in-Space Assembled Telescope (iSAT) Study

- **Chartered by NASA SMD and APD to answer the question:**

  When is it worth assembling telescopes in space rather than building them on the Earth and deploying them autonomously from individual launch vehicles?"

- **Final deliverable is a White Paper to the Decadal Survey Committee in Spring 2019**



- **Activity 1a: *Modularizing a 20 m space telescope***
  - Workshop held at Caltech June 5-7
- **Activity 1b: *Assembling and testing the 20 m modularized telescope in space***
  - Robotics, orbit, launch vehicle, assembly platform
  - Workshop scheduled for October 2-4 at LaRC

2018 ExEP Prioritized Technology List

Exoplanet Exploration Program

Coronagraphs and Starshades

Tech. ID	Technology Title	Impact	Urgency	Trend	2018 Score	2017 Score
	weight:	10	10	5		
CG-2	Coronagraph Architecture	4	4	2	**90**	85
S-2	Starlight Suppression and Model Validation	4	4	2	**90**	90
S-1	Controlling Scattered Sunlight	4	4	2	**90**	90
S-3	Lateral Formation Sensing	4	4	2	**90**	90
S-5	Petal Positioning Accuracy and Opaque Structure	4	4	2	**90**	90
S-4	Petal Shape and Stability	4	4	2	**90**	90
CG-3	Deformable Mirrors	4	4	2	**90**	80
CG-1	Large Aperture Primary Mirrors	4	3	3	**85**	85
CG-6	Mirror Segment Phasing	4	3	3	**85**	85
CG-7	Telescope Vibration Sense/Control or Reduction	4	3	3	**85**	85
CG-9	Ultra-Low Noise Near-Infrared Detectors	4	3	3	**85**	85
CG-5	Wavefront Sensing and Control	4	3	2	**80**	80
CG-8	Ultra-Low Noise Visible Detectors	4	3	2	**80**	80
M-4	Ultra-Stable Mid-IR detector	3	3	4	**80**	
M-3	Astrometry	3	3	3	**75**	
CG-4	Data Post-Processing Algorithms and Techniques	4	2	2	**70**	70
CG-10	Mirror Coatings for UV/NIR/Vis	3	3	2	**70**	70
M-2	Space-based Laser Frequency Combs	3	3	2	**70**	
CG-13	Ultra Low-noise Mid-IR detectors	2	3	4	**70**	
M-1	Extreme Precision Ground-based Radial Velocity	2	3	3	**65**	75
CG-14	Mid-IR Large Aperture Telescopes	2	3	3	**65**	
CG-15	Mid-IR Coronagraph Optics and Architecture	2	3	3	**65**	
CG-16	Cryogenic Deformable mirror	2	3	3	**65**	
CG-12	Ultra-Low Noise UV Detectors	2	3	2	**60**	60

Mass measurement to be advanced?

Mid-IR interferometry technology next decade?